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The Observed and Predicted Spatial Distribution of Milky Way Satellite Galaxies

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ABSTRACT

We review evidence that the census of Milky Way satellites similar to those known may be incomplete at low latitude due to obscuration and in the outer halo due to a decreasing sensitivity to dwarf satellites with distance. We evaluate the possible impact that incompleteness has on comparisons with substructure models by estimating corrections to the known number of dwarfs using empirical and theoretical models. Under the assumption that the true distribution of Milky Way satellites is uniform with latitude, we estimate a 33% incompleteness in the total number of dwarfs due to obscuration at low latitude. Similarly, if the radial distribution of Milky Way satellites matches that of M31, or that of the oldest sub-halos or the most massive sub-halos in a simulation, then we estimate a total number of Milky Way dwarfs ranging from $1-3$ times the known population. Although the true level of incompleteness is quite uncertain, the fact that our extrapolations yield average total numbers of MW dwarfs that are realistically $1.5-2$ times the known population, shows that incompleteness needs to be taken seriously when comparing to models of dwarf galaxy formation. Interestingly, the radial distribution of the oldest sub-halos in a ΛCDM simulation of a Milky Way-like galaxy possess a close match to the observed distribution of M31's satellites, which suggests that reionization may be an important factor controlling the observability of sub-halos. We also assess the prospects for a new SDSS search for Milky Way satellites to constrain the possible incompleteness in the outer halo.

Key words: galaxies: haloes — galaxies: Local Group — galaxies: dwarf — methods: N-body simulations

1 INTRODUCTION

The currently favored Λ + cold dark matter (ΛCDM) cosmological model successfully reproduces many of the observed large-scale properties of the Universe, including the properties of the Cosmic Microwave Background recently observed by WMAP (Spergel et al. 2003), the number, size and clustering of galaxy clusters (e.g. Eke et al. 1996; Zehavi et al. 2002), and the evolution of galaxy cluster counts (Rosati et al. 2002). However, several major discrepancies between the predictions of ΛCDM and the observed properties of the Universe on small scales have presented challenges to the paradigm. One outstanding challenge is that Cold Dark Matter models predict over an order of magnitude more low mass, dark matter halos around the Milky Way than the number of observed satellite dwarf galaxies. This discrepancy was first pointed out by Kauffmann et al. (1993), and was later confirmed by high resolution N-body simulations (Klypin et al. 1999; Moore et al. 1999; Font et al. 2001).

Within the ΛCDM framework, a plausible explanation for the discrepancy between the number of predicted sub-halos and observed satellites lies within baryonic physics. The fraction of dark matter halos with $v_c \lesssim 50$ km sec^{-1} that may host a luminous galaxy can be significantly reduced by reionization, feedback, and/or tidal effects (Dekel & Silk 1986; Efstathiou 1992; Thoul & Weinberg 1996; Quinn et al. 1996; Bullock et al. 2000, 2001; Benson et al. 2002; Susa & Umemura 2004; Dijkstra et al. 2004, among others). These baryonic processes are difficult to model. Therefore, the exact extent to which each effects the present day luminosity of dark matter

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sub-halos remains uncertain. A comparison of the total number and the radial distribution of predicted visible satellites with that of the observed Milky Way satellites may provide a test of the feasibility of particular models (e.g. Taylor et al. 2003; Kravtsov et al. 2004).

A number of the above implementations of baryonic physics have been able to reproduce the observed Milky Way dwarf population. Unfortunately, existing comparisons are rendered less meaningful by the uncertain completeness of the Milky Way dwarf satellite population. Due to incompleteness, the observed satellites may not reflect the properties of the underlying population. Models that provide a good match to the current observations may, therefore, actually underpredict the underlying population.

Past searches for Milky Way companions, although very successful, suffer from unavoidable observational biases that could lead to an undercounting of Milky Way satellites both at low Galactic latitudes and at large (> 100 kpc) distances (see §3 for discussion). Furthermore, the extent of these possible biases is not well understood due to a lack of systematic analyses (however, see Kleyna et al. 1997 for a systematic analysis of their survey's sensitivity). Willman et al. (2002) are currently implementing a new search for resolved Milky Way dwarf satellites in the Sloan Digital Sky Survey data. In contrast to past surveys, this search is sensitive to dwarfs similar to and much fainter than any among the known population, at any distance out to the Milky Way's virial radius. The SDSS may thus provide the means to evaluate the possibility of undercounting in the outer halo.

In light of the new Willman et al survey, we reevaluate the evidence for incompleteness to Milky Way satellites similar to those in the known population and highlight the possible impact of such an incompleteness on comparisons with substructure models. In §2, we describe the N-body cosmological simulation of a Milky Way like galaxy that we use to compare with observations. In §3, we review observational evidence for bias in the census of Milky Way companions and estimate the possible number of undetected galaxies similar to those known, based on primarily observational arguments. In §4, we compare the radial distribution of Milky Way dwarfs with that of both the oldest and highest v_c dark matter sub-halos of the simulated galaxy. We use this comparison both to demonstrate how well radial distributions may be used to distinguish between models and to underscore the possible impact of observational bias on such a comparison. Finally, in §5 we estimate the number of dwarfs similar to the known population that the Willman et al. (2002) survey could detect and still be consistent with either of the two models that we consider.

2 THE SIMULATION

Reed et al. (2003) recently simulated the formation of a Milky Way-like disk galaxy in a ΛCDM Universe. They performed a dark matter (DM) only simulation of a Milky Way sized galaxy halo, using PKDGRAV (Stadel 2001). In the following, we use "DMgal" to refer to this galaxy. The details of this simulation are in Governato et al. (2002), but we summarize its properties here. They adopted $\Omega_0 = 0.3$, $\Lambda = 0.7$, $h = 0.7$, $\sigma_8 = 1$, and $\Gamma = 0.21$, where Γ is the shape parameter of the power spectrum. Table 2 lists the main parameters of the simulation at z = 0. We use $\delta\rho/\rho \sim 100$ to define the virial radius of the galaxy (Eke et al. 1996).

	R_{vir} kpc	M_{vir} $M_\odot$	N_{dark} within R_{vir}	M_{dark} $M_\odot$	ϵ kpc
DMgal	365	$2.9 \cdot 10^{12}$	864,744	$3.3 \cdot 10^6$	0.5
cl1c6	1700	$2.9 \cdot 10^{14}$	4,568,456	$6.3 \cdot 10^7$	1.25

Table 1. Simulation Data

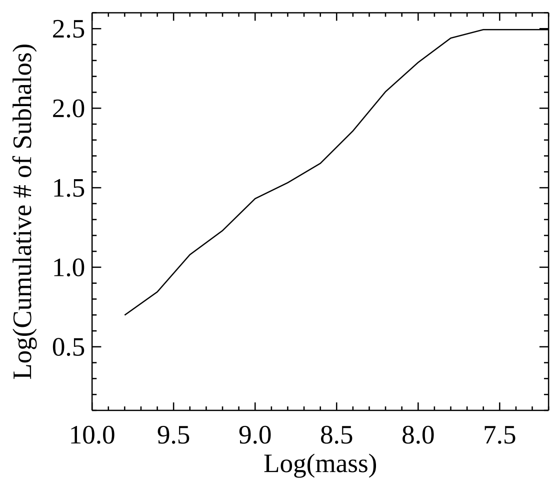

Figure 1. The cumulative number of sub-halos within R_{vir} as a function of mass in a dark matter only ΛCDM simulation of a 3 $\cdot\, 10^{12} M_\odot$ galaxy described in Governato et al. (2002).

To identify DMgal's sub-halos, we use the SKID[1] halo finding algorithm with a linking length of both 3 kpc and of 2 kpc. We used the smaller linking length to include small halos that are missed by the longer linking length. Figure 1 shows the resulting cumulative number of dark matter sub-halos as a function of mass. The cumulative number of DMgal's sub-halos scales roughly as M^{-2} and does not flatten until masses below 10^8 $M_\odot$.

We compare the radial distribution of DMgal's sub-halos with that of a higher resolution galaxy cluster simulation, 'cl1c6', to ensure the number of sub-halos at small radii is not resolution limited. Table 2 includes the properties of cl1c6 from Reed et al. (2003). Figure 2 shows that the two radial distributions are consistent with each other, and also closely match that of the higher resolution dark matter galaxy in Stoehr et al. (2003), demonstrating that the radial distribution of DMgal's sub-halos is not significantly affected by overmerging.

[1] http://www-hpcc.astro.washington.edu/tools/skid.html

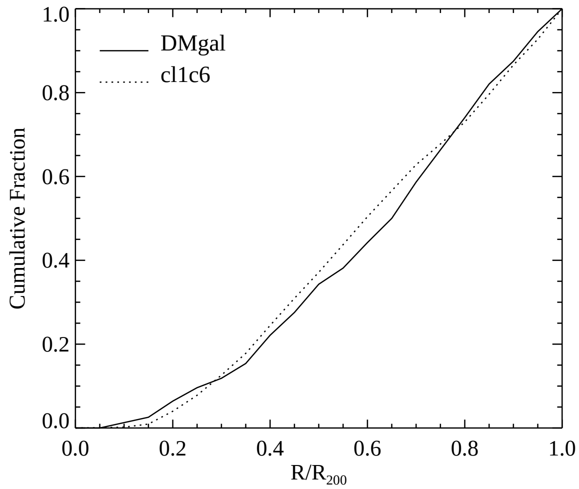

Figure 2. The radial distribution of dark matter sub-halos, in the high resolution, dark matter only simulation described in Governato et al. (2002), as compared to that of a higher resolution simulation of a galaxy cluster (Reed et al. 2003).

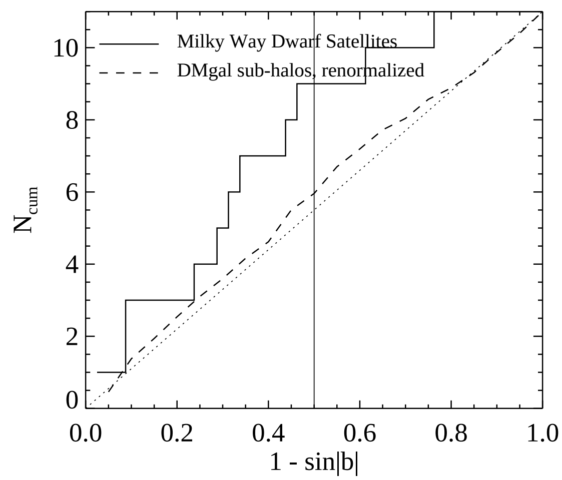

Figure 3. The cumulative number distribution of Milky Way satellites as a function of Galactic latitude, where low values of 1 - sin$|b|$ are toward the Galactic poles. The dotted line shows a uniform spatial distribution of 11 dwarfs. The dashed line shows the latitude distribution of DMgal sub-halos, assuming that galaxy disks are perpendicular to the major axis of their dark matter halos and renormalized to the total number of Milky Way satellites. The vertical line shows where 50% of the cumulative distribution would lie, for a uniform population. The asymmetry in the distribution implies that 7 $\pm$ 2 satellites, similar to the known Milky Way satellites, may lie undetected at low b. Based on Figure 2b from Mateo (1998).

3 OBSERVATIONAL EVIDENCE FOR INCOMPLETENESS IN THE MILKY WAY DWARF GALAXY CENSUS

There is observational evidence that the census of Milky Way companions may be incomplete at low Galactic latitudes and at Galactocentric distance $\gtrsim$ 100 kpc due to observational biases. In this section, we discuss these possible incompletenesses and crudely estimate a reasonable correction to the currently known number of dwarfs.

3.1 Incompleteness at Low Galactic Latitude

The increased extinction and stellar foreground toward the Galactic disk severely limit the detectability of dwarfs that may lie at low latitude. This bias could account for the observed asymmetric distribution of Milky Way satellites with latitude, pointed out by Mateo (1998). Figure 3, based on Figure 2b in Mateo (1998), shows the cumulative number distribution of the 11 Milky Way dwarf satellites as a function of Galactic latitude. If the true distribution of dwarfs around the Milky Way is uniform with latitude, then their cumulative number will increase linearly from the Galactic poles with increasing 1 - sin$|b|$ (Mateo 1998). The dotted line in Figure 2 thus shows the predicted distribution of a uniform population of 11 dwarf satellites. For reference, the solid line shows where 50% of such a distribution would lie.

Assuming a uniform latitude distribution, the fact that 9 of the 11 known dwarfs have been detected at Galactic latitudes above the expected 50% point implies a total of 18 $\pm$ 4 galaxies with similar properties to the known dwarfs. This number represents a crude approximation of the effect of observational bias at low latitude, as we ignore the possibility that Milky Way dwarfs are not randomly distributed, but rather are distributed in 'dynamical families' (Majewski 1994; Fusi Pecci et al. 1995; Lynden-Bell & Lynden-Bell 1995; Palma et al. 2002).

Another uncertainty in the above estimate is that the intrinsic distribution of dwarfs may not be uniform. For example, Karachentsev (1996) found that M31's satellites follow an elongated distribution. However, the 3 M31 satellites discovered since then decrease the extent of the spatial asymmetry (Armandroff et al. 1999). There is also some observational evidence that the satellites of isolated disk galaxies may be biased to lie at $|b| > 30$ (Holmberg 1974; Zaritsky et al. 1997; Zaritsky & Gonzalez 1999). However, it is unclear how this "Holmberg effect" observed in isolated galaxies may translate to galaxies in richer environments, such as the Local Group. Furthermore, this effect has only been observed in satellites with d $<$ 50 kpc (Holmberg 1974) or 300 $<$ d $<$ 500 (Zaritsky et al. 1997), and has only been reproduced in one published numerical simulation of a disk galaxy (Peñarrubia et al. 2002). Knebe et al. (2003) recently showed that the orbits of simulated galaxy cluster sub-halos are biased to lie along the major axis of the cluster, due to infall along filaments. They hypothesized that if galaxy disks are perpendicular to the major axis of their dark matter halos, that the bias they observe in simulated clusters may explain the Holmberg effect.

We computed the latitude distribution of DMgal's subhalos to investigate whether the non-uniformity seen in the Knebe et al. (2003) cluster simulations is also seen in our galaxy simulation. We determined the latitude of each subhalo assuming that galaxy disks are perpendicular to the major axis of their associated dark matter halos. To determine the shape and orientation of DMgal, we used the

moments command in TIPSY[2], based on the technique described in Katz (1991). The latitude distribution of DMgal's sub-halos, overplotted on Figure 3, does not have the asymmetry seen in that of Milky Way satellites. The fact that the latitude distribution of DMgal's sub-halos is uniform shows that the Knebe et al. (2003) result is not necessarily universal, and that Milky Way satellites are possibly distributed uniformly with latitude.

The very recent discoveries of low latitude, low surface brightness stellar structures around the Milky Way (Monoceros stream: Newberg et al. 2002; Yanny et al. 2003; Rocha-Pinto et al. 2003; Ibata et al. 2003; Crane et al. 2003; Martin et al. 2004; TriAnd: (Rocha-Pinto et al. 2004)) also lend strength to the interpretation that the apparently asymmetric latitude distribution is at least partially due to observational bias. It is possible that each of these streams may be associated with a low mass dwarf galaxy that is currently undergoing tidal disruption. However, a distinct core has not been clearly detected in either system. Such systems would not necessarily have been identified as a 'dwarf galaxy' or 'dark matter halo' in theoretical predictions of the expected Milky Way satellite population. Because our analysis is both based on and intended to be compared with such theoretical predictions, we do not include these systems in our quantitative analysis.

We thus conclude that the asymmetric distribution of Milky Way dwarfs with latitude implies a realistic incompleteness in the Milky Way dwarf census of $\sim$ 33%, with a range from 0% to 50% including variance due to Poisson noise, the fact that satellites may not be randomly distributed, and the fact that the evidence discussed above shows that there may be intrinsic asymmetry in the distribution.

3.2 Incompleteness in the Outer Galactic Halo

In this section, we use the known satellite population of M31 to crudely estimate the number of Milky Way satellites similar to those in the known population that may have been missed in past surveys.

Surveys for Local Group dwarf galaxies based on diffuse light have been limited to central surface brightnesses brighter than 24 – 25 mag arcsec^{-2}. However, surveys for overdensities of resolved stars have been able to identify five nearby ($\lesssim$ 110 kpc) Milky Way dwarf satellites with μ_0 fainter than 25 mag arcsec^{-2} (Wilson 1955; Cannon et al. 1977; Irwin et al. 1990; Ibata et al. 1994). Three of these five were found by visual inspection, one was found serendipitously, and one was found as an excess in total number density of stars in scans of UKST plates. Such surveys are less sensitive to outer halo satellites (100 - 250 kpc) because far fewer of their stars are resolved than in more nearby satellites. These surveys thus would have been unable to detect distant (> 100 kpc) dwarfs as faint as those detected more nearby. Such faint, outer halo systems thus lie in a "blind spot" of past surveys. Kleyna et al. (1997) did perform a systematic and automated survey for resolved Milky Way companions over 25% of the sky that was sensitive to any of the known dwarfs to distances of 140 kpc. However, 85% of the volume of the Milky Way's halo lies beyond 140 kpc, leaving open the possibility of undercounting in the outer halo.

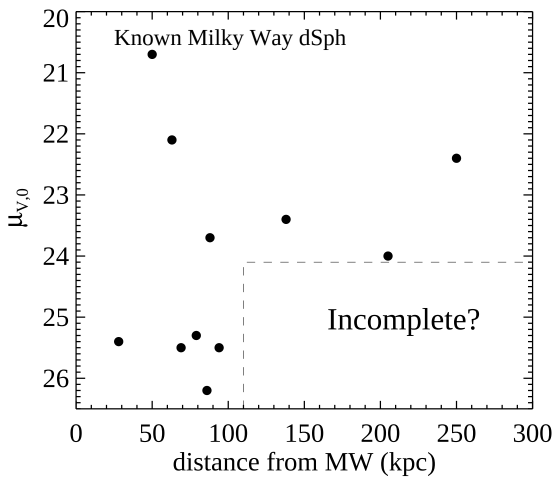

Figure 4. The V-band central surface brightnesses of the Milky Way dwarf companions as a function of their distance. The dwarf census in the boxed region may be incomplete because past surveys for Milky Way dwarf satellites were less sensitive to galaxies in the outer halo. Data from Mateo (1998) and Grebel et al. (2003). This figure is based on Figure 6 from van den Bergh (1999).

This observational bias may explain the notable dearth of Milky Way dwarf galaxies more distant than 110 kpc with surface brightnesses fainter than 24 mag arcsec^{-2}, as pointed out by van den Bergh (1999). Figure 4, based on Figure 6 in van den Bergh (1999), shows the distribution of central surface brightnesses and Galactocentric distances of known Milky Way satellites. Bellazzini et al. (1996) also noted the apparent trend of surface brightness with Galactocentric distance for Milky Way satellites, not including the Magellanic Clouds. They attributed the trend to a true physical effect, due to the Galactic tidal field, rather than to an observational bias.

Using N-body simulations, Mayer et al. (2001) showed that tidal stirring from the Galactic tidal field can serve to decrease the surface brightness of dwarf galaxies. Qualitatively, this effect could result in a lack of ultra-low surface brightness satellites at Galactocentric distances smaller than 100 kpc. It is possible to test this alternative hypothesis by looking for a trend between surface brightness and distance in M31 dwarf satellites. Because M31 and its satellites lie at a common distance and are detected by diffuse light, one expects the satellites to be uniformly sampled with radial distance from M31 and thus not to see a positive trend in their $\mu_{V,0}$ with radial distance due to the bias described above. One instead expects to see a distance independent cutoff at the surface brightness corresponding to the limiting sensitivity of existing sky survey data. Figure 5 shows the distribution of central surface brightness and Galactocentric distances of known M31 companions. The lack of any radial trend in the dwarf companions to M31 suggests that tidal interactions alone do not account for the relative overabundance of dwarfs fainter than 24 mag arcsec^{-2} in

[2] http://www-hpcc.astro.washington.edu/tools/tipsy/tipsy.html

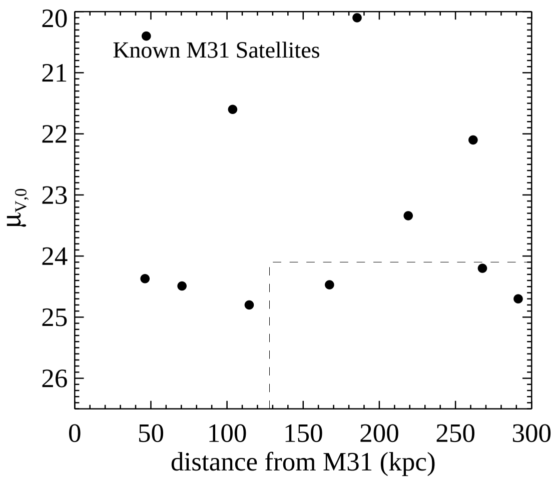

Figure 5. The V-band central surface brightnesses of the M31 dwarf companions as a function of their distance. M32 is not on this plot because it is brighter than the plotted range. Data from Mateo (1998) and Grebel et al. (2003). The region corresponding to that of a possible incompleteness in the known Milky Way population is outlined by the dotted box. There is no evidence for incompleteness at low surface brightness and large radii, as was seen in the Milky Way dwarf satellite distribution. The cutoff seen around $\mu_{V,0} = 25$ mag arcsec^{-2} may be due to the limiting surface brightness of surveys for Local Group dwarfs.

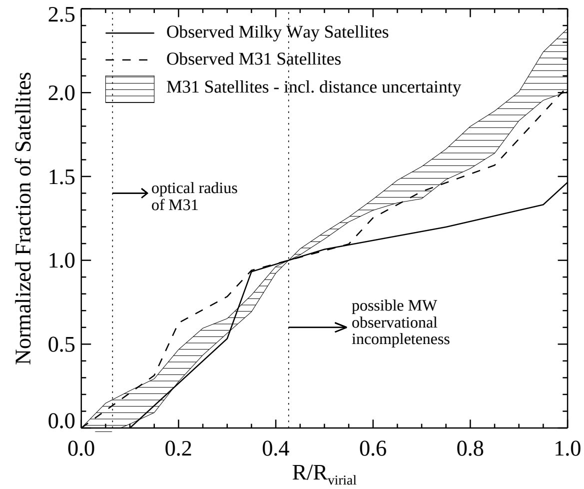

Figure 6. Radial distributions of dwarf satellites to the Milky Way and M31. The radial distribution of M31 satellites, taking distance measurement errors into account, is overplotted. For reference, the optical radius of M31, and the radius beyond which there is evidence for observational incompleteness in the Milky Way dwarfs are also overplotted.

the inner halo of the Milky Way. However, this comparison is inconclusive due to the fact that the 5 ultra-faint Milky Way companions closer than 100 kpc may have been thus far undetectable around M31.

Another way to evaluate the possibility of undercounting in the outer halo is to compare the radial distribution of Milky Way satellites with that of M31 satellites and see if they differ at large radii. Figure 6 shows the radial distributions of both M31 and Milky Way satellites after normalizing the Galactocentric distances of the dwarfs from each galaxy by their parent galaxy's virial radius, R$_{vir}$ (258 kpc for the Milky Way and 280 kpc for M31 from Klypin et al. 2002). We also normalized the radial distributions to the cumulative number of dwarfs within 0.43 R$_{virial}$, the most uniformly sampled volume around the Milky Way. We overplot the optical radius of M31, to show that obscuration by the disk of M31 does not cause a substantial undersampling of its nearby dwarf satellites.

Figure 6 shows that M31 satellites are less biased to lie at small radii than Milky Way satellites, as expected if Milky Way satellites are undercounted at large radii. However, M31 satellites have distance measurement uncertainties that range from 25 to 70 kpc (Grebel et al. 2003), which may affect the utility of this comparison. We thus simulate the effect of M31 and M31 satellite distance uncertainties on the measured radial distribution of M31 satellites. To do this, we calculate a radial distribution for each of 1000 samples of M31 satellites with distances drawn from Gaussians with the published distance uncertainties of each satellite. The distance to M31 is also permitted to vary for each sample, according to its distance measurement uncertainty (Stanek & Garnavich 1998). The 1-sigma range of resulting radial distributions is overplotted on Figure 6. This 'simulated' M31 radial distribution is systematically less biased to small radii than the original M31 distribution, making it even less consistent with the observed Milky Way distribution. This unusual result stems from the fact that 7 of M31's 12 satellites have measured distances within 30 kpc of M31's distance. Along a line of sight near M31, a satellite with dist$_{sat-MW}$ $\sim$ dist$_{M31-MW}$ has the minimum dist$_{M31-sat}$ possible. Therefore, distance errors serve only to increase dist$_{M31-sat}$ for a majority of M31 satellites.

A Kolmogorov–Smirnov test shows that Milky Way satellites are formally consistent with being drawn from the same distribution as the M31 dwarfs (not accounting for distance uncertainties). This similarity of the radial distributions suggests that the extent of outer halo undercounting may not be substantial. However, the facts that: *i)* the radial distribution of Milky Way satellites flattens dramatically at the intermediate distances beyond which observational bias would lead to an undercounting of Milky Way dwarfs and *ii)* the two populations have such different surface brightness distributions at the faint end, makes the case for inconsistency stronger. Furthermore, distance uncertainties reduce the compatibility of the Milky Way's and M31's radial distributions.

To quantitatively assess the possible number of missed Milky Way satellites, we crudely estimate the number of additional dwarfs necessary at $d \gtrsim 100$ kpc for M31 and the MW to have the same fraction of satellites within $0.43R_{vir}$, the most uniformly sampled volume around the Milky Way. If we assume that the Milky Way population is uniformly sampled within 110 kpc and, like M31, that half of Milky Way dwarfs lie beyond 110 kpc ($0.43R_{vir}$), we expect a total of 15 – 18 $\pm$ 4 Milky Way dwarfs. The range in numbers is from the range in radial distributions consistent with distance uncertainties. These upper and lower limits correspond to a range of 0 – 11 undetected dwarfs more distant

method	tot	$tot_{b,corr}$	undet	$undet_{b,corr}$
M31	15 - 18 ± 4	25 - 29 ± 5	4 - 7 ± 4	14 - 18 ± 5
oldest	14 ± 4	22 ± 5	3 ± 4	11 ± 5
highest v_c	20 ± 4	33 ± 6	9 ± 4	22 ± 4

Table 2. Predicted Number of Milky Way Dwarfs With Properties Similar to the Known Population

than 110 kpc. However, these numbers do not account for the possible incompleteness in the known Milky Way population at low latitude, discussed in §3.1. Accounting for a 33% incompleteness at low b increases the above expected total number of MW dwarfs to 25 – 29 ± 5. Thus, we calculate a total combined average incompleteness from both Galactic obscuration and undersampling in the outer halo of $\sim$ 50%, with a possible range of 0% to 66% incompleteness, including Poisson variation and uncertainty in the true distribution of satellites with latitude. We emphasize that these numbers only account for dwarfs with properties similar to the known population and do not extrapolate to a population of even fainter dwarfs, should they exist.

The robustness of these estimated numbers is affected by the small numbers of dwarfs (and hence the large possible fluctuations from the underlying populations) and the fact that the known population of M31 may not represent the underlying distribution of dwarfs down to 26 mag arcsec^{-2}. However, these numbers are simply intended to underscore the necessity of considering incompleteness when matching models to observations, and to provide a prediction that may be testable by the Willman et al. (2002) survey for Milky Way dwarf companions. Several marginal cases of additional Milky Way dwarf companions have been identified within 110 kpc, such as the Monoceros stream (Yanny et al. 2003, among others) and ω Cen (Lee et al. 1999; Dinescu et al. 1999; Majewski et al. 2000). Including these sources in the analysis would exacerbate the discrepancy in the radial distributions and result in a larger predicted possible number of undetected satellites.

The quantitative predictions for the number of Milky Way dwarf satellites with properties similar to the known population are summarized in Table 2. The first column gives the distribution the Milky Way was compared to (in this case, M31). The next 4 columns give the predicted values for: the total number of MW dwarfs assuming no incompleteness at low latitude, the total number of MW dwarfs assuming a uniform distribution in latitude, the undetected number of dwarfs beyond 110 kpc assuming no incompleteness at low latitude, and the total undetected number of dwarfs (both at low b and in the outer halo) assuming a uniform distribution.

4 THE SPATIAL DISTRIBUTION OF GALAXY SUB-HALOS IN ΛCDM SIMULATIONS

In this section, we compare the observed radial distributions of Milky Way and M31 satellite galaxies with the radial distributions predicted by two different simplistic substructure models applied to the Milky Way-like galaxy from a the high resolution ΛCDM cosmological simulation described in §2. We use these two models to highlight the impact of a possible incompleteness on the robustness of such comparisons. We then estimate the number of additional Milky Way dwarfs possible at $d \gtrsim 110$ kpc for the observed and the model distributions to be consistent.

Following Taylor et al (2003), we use either the oldest or the highest v_c sub-halos to characterize two popular substructure scenarios. The oldest sub-halos would preferentially be observable as luminous satellite galaxies in a scenario where reionization is the dominant physics that effects the observability of low mass sub-halos. In this scenario, low mass sub-halos that form after reionization cannot accrete as much neutral gas as halos that formed before reionization, if they can accrete any at all, making it difficult for sub-halos that collapse after reionization to ever form stars. On the other hand, Stoehr et al. (2002) and Hayashi et al. (2003) recently suggested that the highest v_c sub-halos (at z = 0) may preferentially be observable as Milky Way satellites, if the circular velocities of the observed Milky Way satellites have been grossly underestimated. In that scenario, a combination of reionization, feedback, and tidal effects could have rendered all of the less massive sub-halos thus far unobservable. Although these two models clearly are not complete descriptions of the physics that affects sub-halo luminosity, they are sufficient for the purposes described above.

4.1 Identifying Oldest and Highest v_c Sub-halos

To select the oldest sub-halos, we reconstruct the trajectory of each sub-halo within R_{vir} of the galaxy at z = 0 back to z = 9.7. We used the mass history of each sub-halo to interpolate the time at which each contained both 50% and 25% of its peak mass. A sub-halo was the progenitor, P_b, a of a sub-halo, S_a if it contained the highest fraction of the number of particles in S_a. If multiple halos contained > 10% of S_a's particles, we selected P_b as the sub-halo that contributed the highest fraction of its 10 most bound particles to S_a, following De Lucia et al. (2004).

We defined the highest v_c sub-halos as those with the highest peak circular velocities, v_{peak}, at z = 0. The circular velocities are simply determined by $v_c = (GM/r)^{0.5}$, out to each sub-halo's tidal radius. We find that the 15 sub-halos with the highest v_{peak}s at z = 0 include the 12 sub-halos with the highest masses along their past trajectory.

4.2 Radial Distribution of the Oldest and Highest v_c Sub-Halos

Figure 7 shows the radial distributions of the entire DMgal sub-halo population, the oldest and highest $v_{c,z=0}$ sub-halos, and the dwarf populations of the Milky Way and M31. The spread in M31 radial distributions due to distance uncertainties is also overplotted (see §3.2). We used the sub-halos that accreted 50% of their peak mass at the earliest time to define the oldest population. Again, we have normalized the distances by the virial radius of the parent halo to account for differences in the size and mass of the Milky Way, M31 and DMgal. We have also normalized the radial distributions to the cumulative number of dwarfs within 0.43 R_{virial}, the most uniformly sampled volume around the Milky Way. Due to small numbers, KS tests show that all of the plotted distributions, except for that of the entire sub-halo distribution,

are at least marginally consistent with each other. This consistency highlights a potential difficulty in using the radial distribution of a single population to rule out models. However, some of the distributions are much more similar than others, which we discuss below.

This figure shows that sub-halos with the highest peak velocities at z = 0 are biased to lie at smaller radii than the overall sub-halo population. A KS test of the two distributions shows they are not inconsistent with being drawn from the overall sub-halo population with ~30% certainty. This radial bias was also found by Taylor et al. (2003) and Kravtsov et al. (2004) for galaxy sub-halos, and Governato et al. (2001) and Diemand et al. (2004) for the highest v_{peak} sub-halos of galaxy clusters. To understand this radial bias, consider that the radial distribution of the highest v_{peak} sub-halos is very similar to that of the sub-halos with the highest mass along their past trajectories, as stated in §4.1. The sub-halos surviving at small Galactocentric distances at z = 0 are those that were, on average, the most robust to tidal disruption. Sub-halos with the highest masses in the past were both more robust to tidal disruption, and would have experienced dynamical friction that would have reduced their apocenter distances.

The fact that the highest v_c sub-halos have a distribution that is much less biased to small radii than that of even M31's satellites, suggests that the Stoehr/Hayashi model may not be correct. A recent dynamical study by Kazantzidis et al. (2003) reaches the same conclusion. Nevertheless, to evaluate the possibility of using radial distributions to distinguish between substructure models, we compute the number of undetected outer halo Milky Way satellites necessary for the same fraction of them and of the highest v_c sub-halos to lie within $0.43R_{vir}$ (as we did in §3.2). The resulting total number of dwarfs similar to the known population, in the highest v_c sub-halo model, ranges from 20 – 33, depending on the assumed latitude distribution of the satellites. These numbers are summarized in Table 2.

Similar to the highest v_c sub-halos, the oldest sub-halos are biased to lie at smaller radii than the overall sub-halo population, but even more so. In fact, there is a striking similarity between the radial distribution of the oldest sub-halos and the observed satellite galaxies, particularly of M31's. The scatter in the M31 satellites' radial distribution, due to distance uncertainties, reduces its similarity to that of the oldest sub-halos. However, a KS test shows that, at worst, they are consistent with each other at > 80%, which is more than any of the other distributions. The radial distribution of the oldest sub-halos defined by the time they had accreted 25% of their peak mass, rather than 50%, also matches the plotted distribution very closely. We again compute the number of undetected Milky Way satellites necessary in the outer halo for the fraction of Milky Way satellites within $0.43R_{vir}$ to exactly match that of the oldest sub-halos. The numbers are summarized in Table 2.

The close match between the radial distribution of the oldest sub-halos and that of M31 seems to indicate that reionization is a primary factor effecting the observability of sub-halos. However, Kravtsov et al. (2004) used a more detailed approach and found that the observable properties of Galactic satellites are primarily a function of the physics of galaxy formation, rather than reionization. This different result demonstrates that cosmic scatter intrinsic to both observed and simulated satellite distributions may be a large enough effect to make it difficult to distinguish between substructure models solely using a small sample of radial distributions. This potential pitfall is reflected in the fact that the numbers for the 3 different models in Table 1 are all consistent within their Poisson errors.

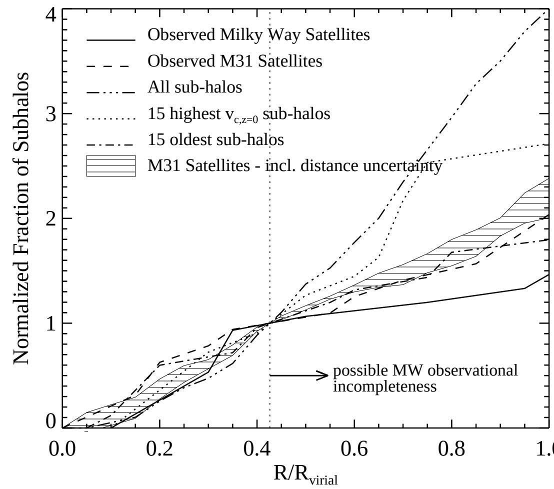

Figure 7. The radial distributions of: dark matter sub-halos of a 3 $\times 10^{12} M_\odot$ galaxy in a ΛCDM dark matter only cosmological simulation (Governato et al. 2002), the 15 highest v_c sub-halos, the 15 oldest sub-halos, and the known Milky Way and M31 dwarf satellites. We also overplot the spread, due to distance uncertainties, of M31 radial distributions (see §3.2). The highest v_c sub-halos are defined as those with the highest v_{peak} at z = 0, and the oldest sub-halos are defined as those that accreted 50% of their peak mass at the earliest time.

5 PREDICTIONS FOR A NEW DWARF GALAXY SURVEY

In this section, we determine if any of the above predictions for the number of undetected outer halo Milky Way satellites similar to those known will be testable by the new SDSS search for resolved dwarf galaxy companions to the Milky Way (Willman et al. 2002). To do this, we calculate the number of undetected dwarfs similar to the known population, but more distant than 110 kpc, that may lie in the SDSS area under various sets of assumptions. Because SDSS only observes at $b > 30$, it cannot constrain incompleteness at low b. The number of predicted dwarfs in the surveyed area is independent of whether we assume a uniform distribution in latitude or assume that the observed distribution in latitude accurately reflects the underlying distribution. We thus compute the number of undetected dwarfs as:

$$f_{|b|>30} \cdot f_{obs,|b|>30} \cdot n_{undet,nocorr}, \quad (1)$$

where $f_{|b|>30}$ is the fraction of satellites observed to lie above $|b| = 30$, $f_{obs,|b|>30}$ is the fraction of $|b| > 30$ sky that SDSS will image, and $n_{undet,nocorr}$ is the number of predicted undetected galaxies with no latitude correction.

When complete, the SDSS will cover $\sim$ 25% of the entire sky. Based on the numbers in Table 2, we expect a total of only 2-3 $\pm$ 1 undetected outer halo dwarfs from the

M31 'model', a total of 1 ± 1 dwarf from the oldest sub-halo model, and a total of 4 ± 2 dwarfs in the highest v_c sub-halo model. In the event of a null detection, the SDSS coverage will not be sufficient to definitively assess whether the underlying radial distribution of MW dwarfs is exactly consistent with any of these three models. However, the detection of a substantial number of outer halo dwarfs would call the "oldest sub-halo" (reionization) model into question. In a future paper, we will assess the number of dwarfs fainter than those in the known population, as predicted by various substructure models, that the new SDSS search should be sensitive to.

6 CONCLUSION

In this paper, we have reviewed evidence for incompleteness in the known Milky Way dwarf satellites with properties similar to those in the known population. This possible incompleteness is due to past observational bias against detecting Milky Way satellites at low latitude and in the outer Galactic halo. Although the level of incompleteness is very uncertain, the fact that an empirical extrapolation from the M31 distribution yields an average total number of MW dwarfs that is 1.5 – 2 times the known population shows that incompleteness needs to be taken seriously when comparing to models of dwarf galaxy formation.

We used the oldest and highest v_c sub-halos of a simulated Milky Way-like galaxy to demonstrate how radial distributions may be used to distinguish between proposed models of dwarf galaxy formation. However, KS tests comparing the radial distributions of the Milky Way, M31, and the oldest sub-halos and the highest v_c sub-halos in simulations show that they are all at least marginally consistent with each other. Interestingly, the M31 distribution is consistent with the oldest sub-halo distribution at $> 95\%$, suggesting that reionization may have a substantial effect on the observabilitiy of sub-halos (however, see Kravtsov et al. 2004). However, small numbers and cosmic scatter permit at least a marginal consistency between a wide range of observations and models. It is thus difficult at present to use radial distributions alone to clearly distinguish between substructure models, although they certainly provide a complimentary test of model predictions. Though faint galaxy membership in other groups is currently controversial, when the satellite populations of galaxies in nearby groups are known more precisely, their radial distributions will provide a stronger discriminant between models. Likewise, a large ensemble of high resolution simulations will allow a more robust assessment of the effects of cosmic scatter and small numbers on the predicted satellite population.

The crude arguments presented in this paper result in predicted total numbers of dwarfs that range from 1 – 3 times the known number, with the most realistic estimates producing an incompleteness in the Milky Way dwarf census of up to 50%. The exact level of incompleteness is strongly dependent on the distribution of Milky Way satellites with latitude. If the Milky Way census is incomplete at the level of 50% or more, then many existing models underpredict the number of luminous Milky Way dwarfs. In particular, models with suppressed small scale power would not produce enough luminous dwarf galaxies, as has already been suggested by Chiu et al. (2001). Note that our derived "total incompleteness" only accounts for dwarfs with properties similar to those known, not any fainter dwarfs, should they exist.

Currently, the largest uncertainty in the known Milky Way population is the underlying distribution of dwarfs with latitude. Before the Milky Way satellite population can yield a meaningful comparison with substructure models, this uncertainty needs to be investigated with more detail than presented in this paper. The average incompleteness in the current census, assuming a uniform distribution in latitude and no other incompleteness, is 33%. Any survey sensitive to faint dwarf satellites at low latitude would thus place very valuable constraints on the Local Galaxy luminosity function.

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